

Modified power rate sliding mode control for robot manipulator based on particle swarm optimization

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ABSTRACT

This work suggests an optimized improved power rate sliding mode control (PR-SMC) to control a 4-degrees of freedom (DOF) manipulator in joint space as well as workspace. The proposed sliding mode control (SMC) aims to improve the reaching mode and to employ an optimization method to tune the control parameters that operate the robotic manipulator adaptively. Inverse kinematics is used to obtain the joint desired angles from the end effector desired position, while forward kinematics is used to obtain the real Cartesian position and orientation of the end effector from the real joint angles. The proposed enhancements to the SMC involve the use of the hyperbolic tangent function in the control law to improve the reaching mode. Added to that, particle swarm optimization (PSO) is used to tune the parameters of the improved SMC. Furthermore, the Lyapunov function is utilized to analyze the stability of the closed-loop system. The proposed enhanced sliding mode combined with the optimization method is applied experimentally on a 4-DOF manipulator to prove the feasibility and efficiency of the proposed controller. Finally, the performance of the suggested control scheme is compared with the conventional power rate SMC in order to demonstrate the enhanced performance of the suggested method.

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1. INTRODUCTION

In recent years, robot manipulators outperform humans in several tasks, where they were able to perform repetitive tasks at the same speeds with a high level of accuracy. Furthermore, robot manipulators can perform tasks that are considered as dangerous for humans. Therefore, the advantages of utilizing manipulators in our life lead to a greater range of tasks, less time wasting and help in producing higher quality products. Operating the robot manipulators is a challenging task due to its nonlinear equations of motion which complicate the task of controlling the manipulator. Several types of controllers used to operate the robotic arm such as sliding mode control (SMC) [1], H-infinity control [2], Finite-time control [3], [4], active disturbance rejection control (ADRC) [5], time-delay control [6], high-order super-twisting sliding mode control [7], optimal control [8]-[9], and predictive control [10]. These control techniques vary from being sensitive to parameters change, hard to find their suitable operating parameters, requiring full knowledge of the model dynamics and having

complex control structure.

SMC is a nonlinear robust controller that was developed by Utkin [11]. The main features of this controller are that it has a quick dynamic response and high robustness against the variation in the plant parameters and external disturbances (uncertainties). However, SMC suffers from an unwanted phenomenon known as "chattering" in the reaching mode. The chattering reduces the control accuracy, leads to high wear of moving mechanical parts, and causes a significant amount of heat dissipation in the electric circuit [12]. Thus, different modifications were added to the conventional version of SMC to overcome the issue of chattering. Hung *et al.* [13] explained multiple versions of SMC were discussed to suppress the chattering and improve the controller performance, one of these techniques is based on the power rate reaching law. Researchers [14], [15] explained an adaptive version of SMC was proposed, where the gain in the reaching mode is adaptively changing based on the error. Furthermore, in [14] the authors suggested a low pass filter in the reaching mode to reduce the chattering. Plestan *et al.* [16] presented two methodologies to adapt the gain of the sliding mode control laws without prior knowledge of the uncertainties and perturbations boundaries, as well as without overestimation of the control gain. According to [17]-[18] the tangent function generates a smooth control action over the bang-bang (*sign*) and the saturation (*Sat*) switching function. Additionally, the tangent function provides smooth input torque, in which *sat* is continuous but not smooth. On the other hand, solving the issue of chattering may increase the number of parameters in the control structure and complicate the tuning process. In order to simplify the tuning process, an optimization algorithm can be adopted to tune the controller parameters, where the objective of the optimization problem is to minimize the difference between the real and desired values. Since it is a nonlinear objective, a meta-heuristic technique such as particle swarm optimization (PSO) is the most appropriate search algorithm. PSO is a swarm-based meta-heuristic that was developed by Kennedy and Eberhart [19]. It mimics the movement of a swarm of birds and fish while they are searching for food (best objective function value). PSO showed good accuracy and fitting performance when compared to other techniques such as genetic algorithms [20].

In the literature, a combination of PID and computed torque control method is used in [21] to operate 2 degrees of freedom (DOF) robot manipulator. Fallaha *et al.* [1] proposed an exponential version of SMC (ESMC) is presented, which adapts the reaching mode exponentially and consequently reduces the chattering level in the control input. ESMC showed a very fast transient response with limited steady-state error. However, the tuning of the control parameters presents a serious challenge due to a high number of parameters. Abougarair *et al.* [22] compared the performance of SMC and proportional integral derivative (PID) based linear quadratic regulator (LQR) operating a two-wheeled self-balanced mobile robot (TWBMR), where SMC proved better tracking performance and robustness than PID-LQR. Zhen *et al.* [23] explained SMC is considered for a class of the uncertain switching system along with external disturbance and time delay. Vu *et al.* [24] proposed a robust adaptive controller to control an excavator arm. The suggested controller consists of two parts; the first part is responsible for keeping the stability of the system, and the second part adapting with the unknown parameters. Bhawe *et al.* [25] described the concept of high order sliding mode control was adopted utilizing the tracking error as the sliding surface for trajectory tracking of a two-link planar manipulator and a three-link articulated manipulator. Mallem *et al.* [26] explained a combination of global fast sliding mode control strategy and radial basis function (RBF) algorithm is used to approximate the uncertain nonlinear function controlling a mobile robot. Rezaee [27] proposed a model predictive control is suggested to operate a mobile robot, where the controller is formulated as an optimal control problem. Taeib and Chaari [28] implemented PSO algorithm to obtain the optimal parameters of a PID controller for a nonlinear multiple-input multiple-output (MIMO) system.

The main contribution of this paper is suppressing the chattering phenomenon of SMC, along with overcoming the complexity of tuning a high number of control parameters by: i) Modifying the power rate SMC in [13] by utilizing the hyperbolic tangent function (*tanh*) in the reaching mode to overcome the chattering issue; ii) Integrating a PSO algorithm with a Simulink model to tune the parameters of the suggested controller that operates the 4-DOF manipulator module. The robot model in Simulink is identical to the used robot experimentally in this work; and iii) Operating the real robot experimentally based on the obtained parameters through the simulations.

Section 2 in this paper presents the system description and modeling. Section 3 is about the mathematical formulation of classical SMC. Section 4 presents the proposed control scheme. Section 5 presents the experimental results to prove the superiority of the suggested control method over the other methods. Finally, section 6 presents the conclusion.

2. MODEL OF THE SYSTEM UNDER STUDY

The robot used in this work is a 4-DOF robotic arm manipulator, where it is a light-weight robot consist of four inter-linked segments. The robot can be operated through a programmed controller to rotate in three-dimensional space and grasp or release objects with the gripper. Thus, the robot can be used for research purposes to study the kinematics and the dynamics of robotic systems. Figure 1 shows structure of the manipulator [29]. The kinematics is the mathematical representation that describes the motion of points and objects regardless of the forces and torques that cause the motion itself, where it deals with the geometric design that rules the system and the relation between the control parameters and performance of the system in the state space. Inverse Kinematics is the mathematical representation of the required joint configurations that enable the end effector of the robot to perform the desired task.

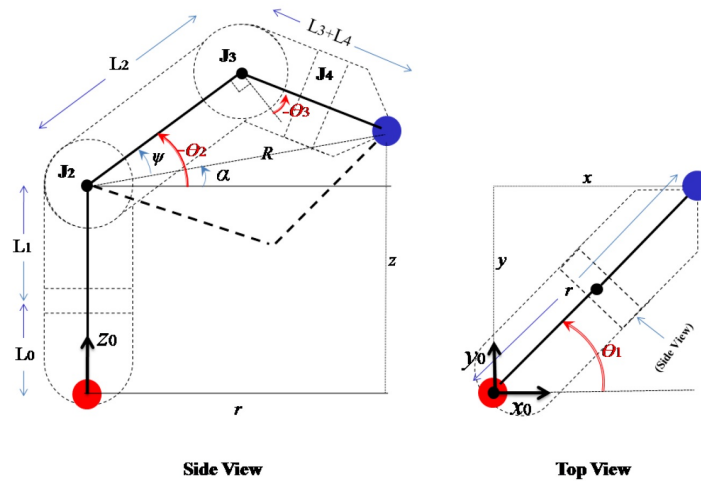


Figure 1. 2D top view of 4-DOF MICO robotic arm [30]

Forward kinematics is used to describe the position of the end – effector with respect to the base coordinates as (1).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} c_1(L_3s_{23} + L_2c_2) + L_4s_{23}c_1 \\ s_1(L_3s_{23} + L_2c_2) + L_4s_{23}s_1 \\ L_1 + (L_3 + L_4)c_{23} - L_2s_2 \end{bmatrix} \quad (1)$$

Where s_i is $\sin\Theta_i$, c_i is $\cos\Theta_i$ and L_i is the arm length.

The unknown joint angles can be found from the position/orientation of the end-effector and applying inverse kinematics using the geometric solution. One possible solution can be given as (2).

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} \text{atan2}(\frac{Y}{X}) \\ \text{atan2}(\frac{X}{c_1}, Z - L_1) - \sigma \\ \text{atan2}(s_3, c_3) \end{bmatrix} \quad (2)$$

$$\frac{X}{c_1} = r \sin(\sigma + q_2)$$

$$Z - L_1 = r \cos(\sigma + q_2)$$

$$\sigma = \text{atan2}(k_2, k_1), k_1 = r \cos(\sigma) \text{ and } k_2 = r \sin(\sigma)$$

$$s_3 = \frac{X^2 + Y^2 + (Z - L_1)^2 - L_2^2 - L_3^2}{2L_2L_3}$$

Where q_4 is independent of the end-effector position, it only affects the orientation of it.

Finding a mathematical relationship between each joint's needed torque and motion is the dynamic modeling. Lagrange approach is used to drive the torque equation. The dynamic model is developed using Lagrange approach as follows [31]:

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) = \tau \quad (3)$$

$$\ddot{q} = -M^{-1}(q)(C(q, \dot{q}) + G(q)) + M^{-1}(q)\tau \quad (4)$$

which q and \dot{q} is the joint angle and velocity, τ is the controlled torque, $M(q)$ is the $n \times n$ inertia matrix of the robot, $C(q, \dot{q})$ is Centrifugal and Coriolis $n \times 1$ vector and $G(q)$ is the gravity $n \times 1$ vector, where n is the number of degrees of freedom for the manipulator. The error dynamics is the regulated variable that is going to be used to build the control law and it is derived from (4), and can be expressed as (5).

$$\ddot{e} = \ddot{q} - \ddot{q}_d = -M^{-1}(C + G) + M^{-1}\tau - \ddot{q}_d \quad (5)$$

3. THE MATHEMATICAL FORMULATION FOR THE CONTROL SCHEME

This section describes in steps the mathematical formulation for the control scheme that operates the robot manipulator. The initial step for designing the sliding mode control is to define the sliding surface S in which the sliding motion will take place [32], S can be expressed as (6).

$$S = \lambda e + \dot{e} \quad (6)$$

Where λ is a constant number that defines the speed of tracking the error. The error e can be defined as (7).

$$e = q - q_d \quad (7)$$

The model dynamics in (3) can be written as follows (8).

$$\ddot{q} = -M^{-1}C - M^{-1}G + M^{-1}u \quad (8)$$

Where the control input u is equivalent to the controlled torque τ . The further step is to design a control law that forces the system state trajectories to reach the sliding surface S (reaching mode) and slides on it toward the equilibrium point (sliding mode), and it is given as (9).

$$U = u_{dis} + u_{eq} \quad (9)$$

Where u_{dis} is the discontinuous control that drives the system states to the sliding surface in the reaching mode by a constant gain, and u_{eq} is the equivalent control that keeps the states on the sliding surface in the sliding mode [13], [32], Figure 2 illustrates the phase plane trajectory of the sliding mode control.

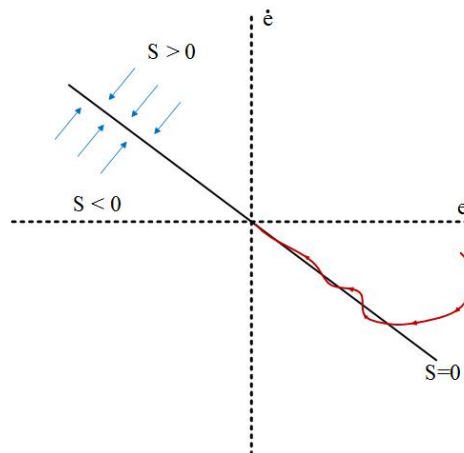


Figure 2. Phase plane trajectory of the sliding mode control

Designing the control law comes from the Lyapunov's function as (10):

$$V = \frac{1}{2} S^T S \quad (10)$$

and the derivative (11).

$$\dot{V} = S^T \dot{S} \quad (11)$$

Where to ensure stability an acceptable choice of \dot{S} (for the case of conventional SMC) can be (12).

$$\dot{S} = -k \operatorname{sign}(S) \quad (12)$$

One of the suggested modification to the conventional SMC is to use a boundary layer around the ideal sliding surface ($S = 0$) to reduce the chattering that comes from using the *signum* function (*sign*) in the reaching mode. The hyperbolic tangent function (*tanh*) has a slower transition rate compared to the discontinuous behavior of the *signum* switching function. Thus, introducing the tangent function to SMC makes (12) re-defined as (13).

$$\dot{S} = -k \tanh(\alpha S) \quad (13)$$

Where α is a constant number that defines the decaying rate of the switching function as shown in Figure 3. Added to that, $k \in \mathbb{R}^{n \times 1}$ and $S \in \mathbb{R}^{n \times 1}$.

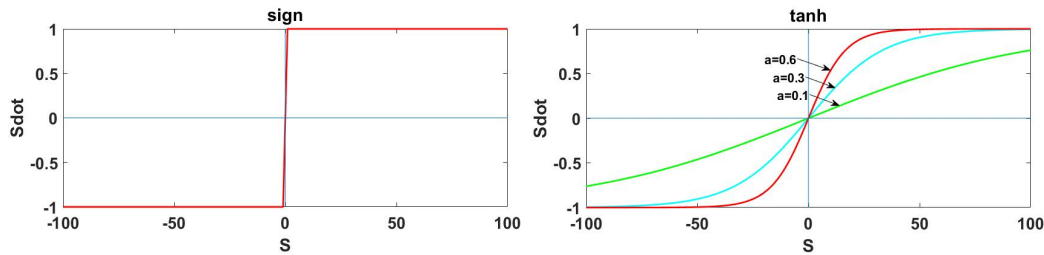


Figure 3. *tanh* and *sign* switching functions

The other modification for SMC is to change the constant gain k in (12) to the power rate reaching law. The power rate reaching law is one of three laws suggested in [13]. The main feature of this law is that it speeds up the reaching time when the system states trajectories are far away from the sliding surface and decreases the speed when the states become closer. The outcome is less chattering in the steady-state response. Therefore, (13) could further be modified to become (14):

$$\dot{S} = -k |S|^\gamma \tanh(\alpha S) \quad (14)$$

which $0 < \gamma < 1$.

Consequently, \dot{V} becomes as (15).

$$\dot{V} = -S^T k |S|^\gamma \tanh(\alpha S) \quad (15)$$

The relation in (15) can be assumed to be negative as far as k is always positive. Then, using the definition of sliding surface in (6) and (5) leads to (16).

$$\begin{aligned} \dot{S} &= \lambda \dot{e} + \ddot{e} \\ \dot{S} &= \lambda \dot{e} + (\ddot{q} - \ddot{q}_d) \\ \dot{S} &= \lambda \dot{e} - M^{-1}C - M^{-1}G + M^{-1}u - \ddot{q}_d = -k |S|^\gamma \tanh(\alpha S) \end{aligned} \quad (16)$$

To express the control law $u = \tau$.

$$M^{-1}u = -k|S|^\gamma \tanh(\alpha S) - \lambda \dot{e} + M^{-1}C + M^{-1}G + \ddot{q}_d$$

$$u = \underbrace{-M\lambda \dot{e} + C + G + M\ddot{q}_d}_{u_{eq}} \underbrace{-Mk|S|^\gamma \tanh(\alpha S)}_{u_{dis}} \quad (17)$$

4. THE OPTIMIZATION ALGORITHM

PSO is an algorithm used to tune the controller parameters in this work. It is a meta-heuristic optimization technique that is based on the social behavior of bird flocking or fish schooling. The algorithm starts by generating a population of random potential solutions known as particles which swarm the search space to find the best (optimal or near-optimal) solution through different iterations. This initial population is generated within the variable boundaries, i.e., lower and upper bounds of the variables. Each particle in the swarm maintains information about its position and velocity and the whole swarm maintains information about the global best position found. Therefore, the particles in the swarm change their search direction according to their historical behaviors (self-best position) and global best position [33].

In this work, PSO is used to optimize the parameters of the PR-SMC. Figure 4 demonstrates the optimization process to find the optimal parameters that operate the robot manipulator to achieve the best performance. The objective function used in this work to minimize the error between the real and desired angle of each joint of manipulator is given as (18).

$$\min E = \sum_{n=0}^{tf} (q_i - q_{di})^2, \text{ for } i = 1 : 4 \quad (18)$$

The controller parameters that were optimized are $\alpha \in [0,1]$, $\gamma \in [0,1]$, $\lambda \in [0,\infty]$, and $k_{1,2,3,4} \in [0,\infty]$.

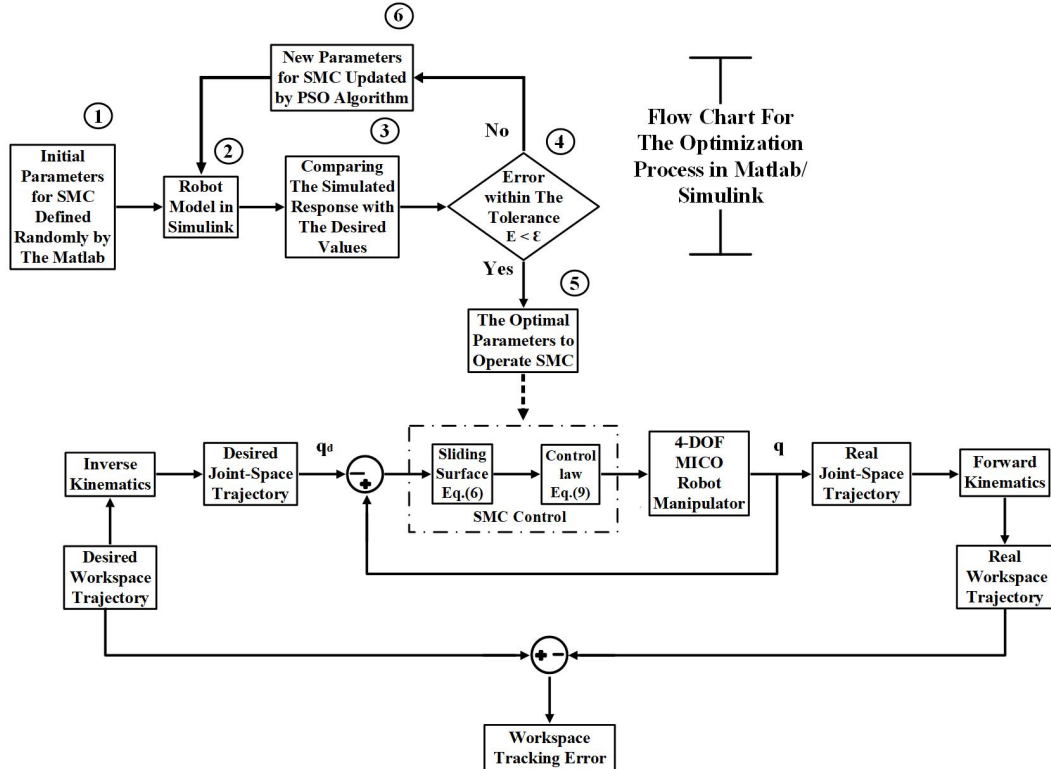


Figure 4. The proposed control scheme

The proposed control scheme in Figure 4 is working based on the following steps: i) Step 1: define random values to the control parameters in Matlab; ii) Step 2: simulate the robot model (offline) in Simulink

with the previously defined parameters; iii) Step 3: compare the simulated response q with the desired values q_d , where this step is performed in Matlab; iv) Step 4: check if the error between the simulated response and the desired values (18) is within the tolerance; v) Step 5: if the error from (18) is within the tolerance then the parameters that operated the robot from step 1 are considered as the optimal parameters, and the next step will be step 7; vi) Step 6: if the error from (18) is not within the tolerance then new parameters are then generated by PSO in Matlab to operate the robot, and the process shall be repeated again from step 2 until finding the optimal parameters; and vii) Step 7: the optimal parameters obtained from PSO are selected to be applied to the real robot experimentally.

5. EXPERIMENTAL RESULTS

The results are carried out using a real robot (Kinova MICO 4-DOF) using Simulink and QUARC open source to implement the suggested controller on the robotic arm. Figure 5 shows the experimental setup for this work.

A data acquisition card (DAQ) is used to link the robot to the Matlab/Simulink software, where the card is reading the input signal from the Matlab/Simulink software to the robot, and write the signal from the actuators sensors that describes the joint's real-time angles. The communication between DAQ, the MICO robot and the Matlab/Simulink is demonstrated in Figure 6. The desired workspace trajectory for the end effector is determined in the Matlab/ Simulink software. The next step is to construct the joint space angles from the workspace using the inverse kinematics. The obtained angles from the inverse kinematics are considered as the desired angles used to build the sliding surface in the suggested controller. The output from the controller is the required torque to operate the joints to reach the desired end-effector position.



Figure 5. Experiment setup

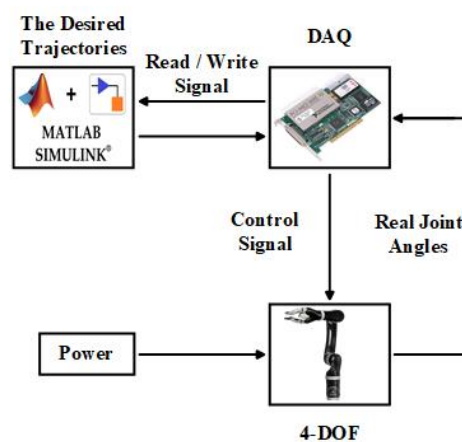


Figure 6. The Communication between DAQ card, Matlab/Simulink and the real robot

The experimental results were carried out in this section to examine the performance of the suggested controller $PR - Tanh$ and $PR - Sign$, where both defined as (19) and (20).

$$u_{PR-Sign} = \underbrace{-M\lambda\dot{e} + C + G + M\ddot{q}_d}_{u_{eq}} - \underbrace{Mk|S|^\gamma \text{sign}(S)}_{u_{dis}} \quad (19)$$

$$u_{PR-Tanh} = \underbrace{-M\lambda\dot{e} + C + G + M\ddot{q}_d}_{u_{eq}} - \underbrace{Mk|S|^\gamma \tanh(\alpha S)}_{u_{dis}} \quad (20)$$

PSO was used in Matlab/Simulink to find the optimal parameters to operate the real robot (offline) for both controllers $PR - Tanh$ and the same parameters applied to $PR - Sign$, to increase the reliability and credibility of this comparison. Once the optimal parameters are obtained, they were applied to the robot in the lab experimentally.

The control parameters used in this work are: $K_1=126.8219$, $K_2=36.5484$, $K_3=66.3047$, $K_4=0$, $\lambda=65.2778$, $\gamma=0.9948$, and $\alpha=0.9902$

Table 1. DH-Parameters

i	α_{i-1}	a_{i-1}	d_i	q_i
1	0	0	D_1	q_1
2	$-\frac{\pi}{2}$	0	0	q_2
3	0	D_2	0	q_3
4	$\frac{\pi}{2}$	0	D_3	q_4
tool	0	0	D_4	0

$${}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & D_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_2 & -c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^2_3T = \begin{bmatrix} c_3 & -s_3 & 0 & D_2 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^3_4T = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ 0 & 0 & -1 & -D_3 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^4_TT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & D_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The kinematic solution is obtained from ${}^0_4T = {}^0_1T \dots {}^3_4T$

$$\begin{aligned} X &= c_1(D_3s_{23} + D_2c_2) \\ Y &= s_1(D_3s_{23} + D_2c_2) \\ Z &= D_1 + D_3 + c_{23} - D_2s_2 \end{aligned} \quad (21)$$

with $q_{23} = q_2 + q_3$

Inverse kinematics:

$$q_1 = \text{atan2}(Y, X) \quad \text{if } D_3s_{23} + D_2c_2 \neq 0$$

$$X^2 + Y^2 = (D_3s_{23} + D_2c_2)^2$$

$$(Z - D_1)^2 = (D_3s_{23} - D_2c_2)^2$$

$$Z = D_1 + D_3 + c_{23} - D_2s_2$$

$$s_3 = \frac{X^2 + Y^2 + (Z - D_1)^2 - D_2^2 - D_3^2}{2D_2D_3}$$

$$c_3 = \pm(1 - s_3^2)^{0.5}$$

$$q_3 = \text{atan2}(s_3, c_3)$$

To find q_2 , we reorganize the position as follows:

$$\begin{aligned}\frac{X}{c_1} &= (D_3 s_{23} + D_2 c_2) = k_1 s_2 + k_2 c_2 \\ \frac{Y}{s_1} &= (D_3 s_{23} + D_2 c_2) = k_1 s_2 + k_2 c_2 \\ Z - D_1 &= D_3 c_{23} - D_2 s_2 = k_1 c_2 - k_2 s_2 \\ \text{where } k_1 &= D_3 c_3 \text{ and } k_2 = D_3 s_3 + D_2\end{aligned}$$

If $c_1 = 0$, consider the 2^{st} and 3^{rd} relations and if $s_1 = 0$, consider the 1^{st} and 3^{rd} relations, then:

$$\begin{aligned}\frac{X}{c_1} &= k_1 s_2 + k_2 c_2 \\ Z - D_1 &= k_1 c_2 - k_2 s_2\end{aligned}$$

To find q_2 , we do the following transformations: $\sigma = \text{atan2}(k_2, k_1)$; $k_1 = r \cos(\sigma)$; $k_2 = r \sin(\sigma)$ and $r^2 = k_1^2 + k_2^2$

finally,

$$\begin{aligned}\frac{X}{c_1} &= r \sin(\sigma + q_2) \\ Z - D_1 &= r \cos(\sigma + q_2) \\ q_2 &= \text{atan2}\left(\frac{X}{c_1}, Z - D_1\right) - \sigma\end{aligned}$$

The only missing variable for the inverse kinematics is q_4 . To find this variable, we should use the orientation of the robot. If we check the elements of this matrix, we have:

$$\begin{aligned}R(3, 1) &= -s_{23}c_4 \\ R(3, 2) &= s_{23}s_4 \\ q_4 &= \text{atan2}\left(\frac{R(3,2)}{s_{23}}, -\frac{R(3,1)}{s_{23}}\right)\end{aligned}$$

If $s_{23} \neq 0$, to reach the toll, we compute ${}^0_T T = {}^0_4 T {}^4_T T$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} c_1(D_3 s_{23} + D_2 c_2) + D_4 s_{23} c_1 \\ s_1(D_3 s_{23} + D_2 c_2) + D_4 s_{23} s_1 \\ D_1 + (D_3 + D_4)c_{23} - D_2 s_2 \end{bmatrix} \quad (22)$$

These last relations will not change the inverse kinematic solution.

Comparing the joint space and workspace tracking of $PR - \text{Tanh}$ and $PR - \text{Sign}$ leads to: i) The optimization method successfully achieved the optimal performance for the control scheme of the robot manipulator experimentally; ii) Both $PR - \text{Tanh}$ and $PR - \text{Sign}$ achieved the required performance in joint space (Figure 7 and Figure 8) and workspace (Figure 9 and Figure 10) using the obtained control parameters from the optimization method; and iii) The joint space tracking error for q_1 in Figure 8 is insignificantly higher for $PR - \text{Tanh}$ than $PR - \text{Sign}$. That is due to the use of Tanh in reaching mode, where it is expected to have this variation from the ideal desired q_1 . However, with the proper optimization that amount of error become very law.

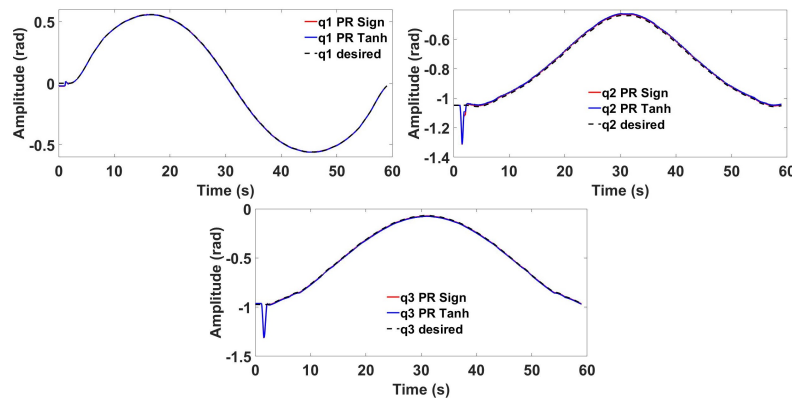


Figure 7. Joint space tracking

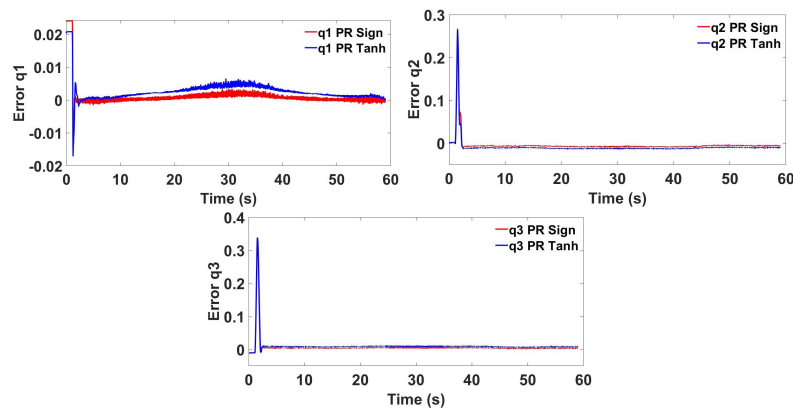


Figure 8. Joint space tracking error

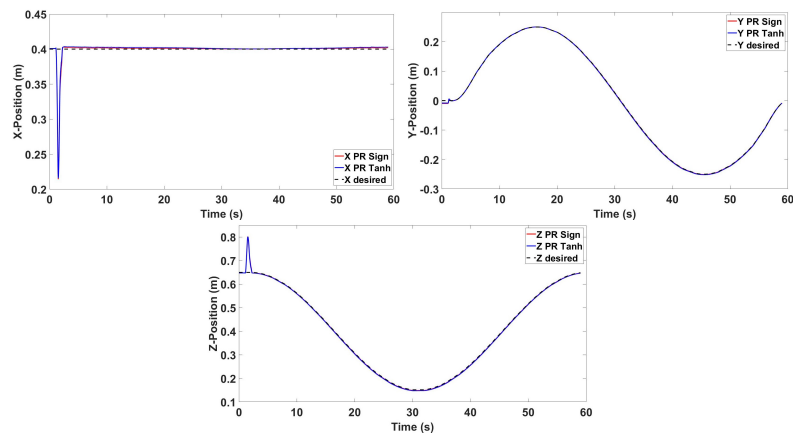


Figure 9. Workspace tracking

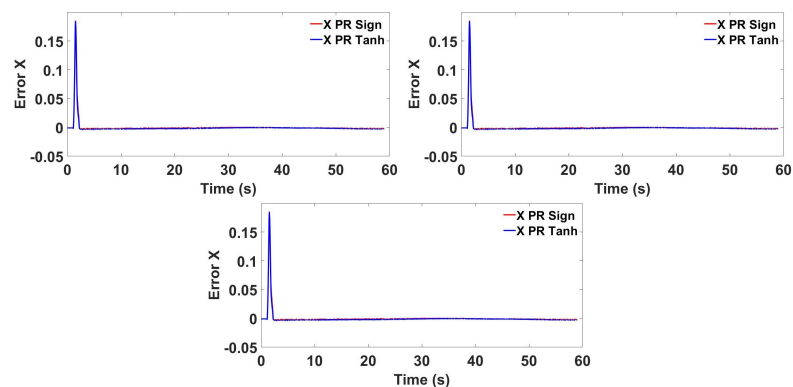


Figure 10. Workspace tracking error

Furthermore, the experimental results for the torque show that the required torque to move the robot joint arm when using $PR - Tanh$ is less compared to $PR - Sign$ as illustrated in Figure 11. That demonstrates the impact of using *sign* in the reaching mode, which generates high amount of chattering despite the fact they both used the same control parameters. Finally, both controllers draw the circle properly as shown in Figure 12, and that proves the fact the optimization is a successful method to tune the parameters of the controller.

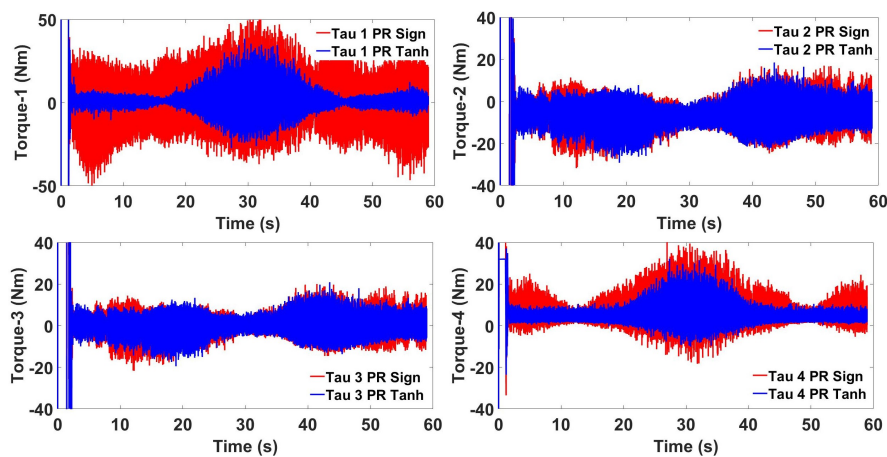


Figure 11. Joints applied torque

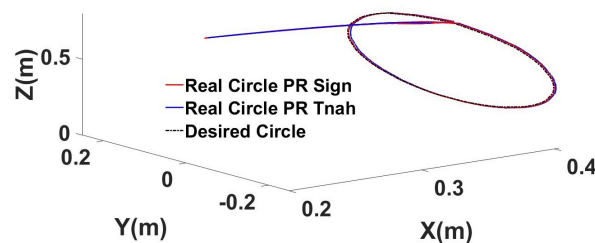


Figure 12. Circular desired and real path

6. CONCLUSION

This research suggested two modifications to the conventional power rate SMC, which are: Using the hyperbolic tangent function to decrease the chattering and to provide smooth continuous control action unlike the signum function. Using PSO to optimize the parameters of the SMC to achieve the optimal performance.

The suggested controller overcomes the complexity of tuning a high number of parameters and provided further improvement by using the tangent function to suppress the chattering. This work can further be extended to utilize machine learning along with sliding mode control, or a hybrid approach based on optimization method and machine learning.





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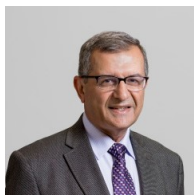
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